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The Cost of the Kyoto Protocol to U.S. Crop Production: Measuring Crop Price, Regional Acreage, Welfare, and Input Substitution Effects

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This study analyzes the impact of implementing carbon permit trading, considered under the Kyoto Protocol, and the subsequent expected increase in energy and resource prices on U.S. crop production. The focus is on input substitution, net farm income, regional crop acreage, and crop prices. The analysis is carried out with a calibrated mathematical programming model which covers the major crops produced in the 48 contiguous states on a regional basis. The model accounts for both the variable inputs and the allocatable inputs of land and irrigation water, and it permits input substitution when farmers are faced with external shocks. The results suggest that when energy prices increase, the net cost to the crop-producing sector depends on the farmer's ability to substitute crop inputs and the elasticity of demand for the crops. The impacts of carbon tax cost increases differ significantly among crops and regions. Overall, crop acreage and output decrease, total net revenues increase in most regions, and consumer surplus declines.

Key words: carbon permit trading, CES production function, crop net revenue, input substitution, Kyoto Protocol, regional crop production

Introduction

U.S. agriculture relies heavily on energy use, directly in farm operations and indirectly via the embodiment of energy in such farm inputs as fertilizers, herbicides, and pesticides. For dryland crops, average direct and indirect energy costs account for 19% of the total variable cost, ranging from 10% for soybeans and up to 27% for cotton. For irrigated crops, the total energy cost constitutes an average of 33% of the total variable cost, and ranges from 26% for hay to 51% for sorghum. Irrigated crop production is especially vulnerable to changes in electricity prices. Energy prices in the U.S. are predicted to increase substantially as plans to reduce carbon emissions are implemented to fulfill this country's international obligation under the Kyoto Protocol. It follows that changes in energy prices will have an appreciable impact on farmers' economic behavior.

The objective of this study is to develop a model of the U.S. crop sector and measure the impacts of energy price increases predicted under the Kyoto Protocol on crop production in the U.S. Specifically, we calibrate constant elasticity of substitution (CES)

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production functions for regional crop production and analyze the effects of increases in the prices of four different fuels and electricity on regional cropping patterns, input use, crop prices, and farm net income. The nonlinear optimization model used in the analysis aggregates the 48 contiguous states into 12 regions. Each region is treated as a farming unit using seven inputs to produce nine crops under dry or irrigated cultivation.

When faced with changes in resource costs, farmers simultaneously adjust output decisions on three margins. The first margin (extensive) determines the level of total production, usually measured in terms of output or land use. The second margin (extensive) adjusts crop production between crops, across regions, and between dryland and irrigated production. The third margin (intensive) of adjustment is the ability to substitute inputs within the production of a given crop. The model used in this study requires that all three margins are in equilibrium, and thus represents the full range of substitution available to U.S. crop producers. Failure to account for input substitution would result in an overestimation of any negative impacts of an energy price increase as farmers are prevented from partially offsetting input price increases via input substitution.

In the following section we discuss the motivation for investigating the carbon permit price impacts on U.S. crop production and outline previous research in this area. We also summarize farmers' reactions, historically, to the oil price shocks of the 1970s and 80s. The article proceeds with an introduction of the mathematical programming model, followed by a section devoted to the empirical specification of the model. The results of the analysis are then presented and discussed, and in the final section we provide a summary and our conclusions.

Motivation and Previous Work

The greenhouse phenomenon is a leading global environmental concern. The urgency of the need to reduce the emissions of offending gases, including CO_2, is evident from the large number of countries who signed the United Nations Framework Convention on Climate Change document in 1992. The agreement calls for an average 5.2% reduction from 1990 levels of greenhouse gas (GHG) emissions by 2010. The amount of reduction is different for each country. During the November 1997 negotiations of the Kyoto Protocol, the U.S. agreed to a 7% reduction below its 1990 levels of carbon emissions during the period 2008–2012 (Congressional Research Service). Each signatory country is expected to develop its own strategy for achieving this reduction. Through a series of ongoing annual meetings, participating countries report on the progress they are making in this regard. The implementation of any U.S. plan is contingent on Congressional approval.

The U.S. government's greenhouse gas abatement efforts are likely to rely primarily on market forces rather than on direct command-and-control approaches. The government's intent to use the market approach was articulated during the March 4, 1998, testimony of Janet Yellen, the chair of the President's Council of Economic Advisers, before the House Commerce Committee. The market approach is comprised of policy tools such as a tax on inputs, tax credits, and payment incentives to polluters to invent, innovate, and adapt new technologies and new products. Instead of a direct tax on fuel use, U.S. policy makers envision an environment where the energy sector will be allocated carbon permits in the amount approximating the target reduction, and where trading of such permits will be allowed. Voluntary incentive programs are also likely to play a role in the efforts to reduce GHG emissions, but they should be minor compared to the market approach. A U.S. Department of Energy (1998) study estimates that if carbon permit trading is implemented to reduce U.S. carbon emissions 7% below their 1990 level, in year 2010, ceteris paribus, the carbon permit price will be $348 per ton in 1996 prices, and energy prices will be an average of 30% above their 1996 levels. This increase in energy prices should have a notable impact on all industries, including agriculture.

U.S. agricultural production activities are responsible for only about 6% of the total GHG emitted in the U.S. (U.S. Environmental Protection Agency); consequently, this sector is not likely to be a direct target in the efforts to reduce GHG. Due to its heavy reliance on fossil fuels, however, the U.S. farm sector will nevertheless feel the effect of GHG abatement policies. U.S. farmers' reactions to previous energy price shocks shed some light on how they might react under the Kyoto Protocol.

The oil crises of the early 1970s and 1980s resulted in more than a fourfold increase in total energy prices in the U.S. in little less than a decade (U.S. Department of Energy 1998, table 5). Past experience shows that when faced with significant energy price increases, U.S. farmers seem to adjust rapidly by substituting away from energy-intensive inputs toward less energy-intensive inputs and capital. In their study of energy efficiency and technological change, Uri and Day found that beginning in 1975, there has been a noticeable improvement in farm machinery energy efficiency as farmers substituted capital (in the form of new energy-efficient diesel equipment) for fuel. Gowdy, Miller, and Kherbachi, who investigated energy use in U.S. agriculture, measured a decrease in energy used per dollar of agricultural output from 1972–77. Annual farm cost-of-production shares calculated by Debertin, Pagoulatos, and Aoun show that, from the first oil shock of 1973–74 until 1980, the cost share of land increased while the fertilizer share fell, and the energy share remained about the same. The fact that energy cost share did not change in the face of a large increase in energy prices suggests farmers were reducing energy use. Cleveland calculates that from 1978 to 1990, the direct and indirect energy used in U.S. farms dropped by 33%.

Stout and Nehring found that as energy prices increase, farmers adopt a more well-timed and precise application of chemicals and irrigation water and reduce the acreage of energy-intensive and heavily irrigated crops. Using a macroeconometric model, Christensen and Heady simulated the impacts of a 50% and a 300% increase in the price of diesel fuel on the agricultural sector. Their findings showed that farmers substitute away from fertilizer and machinery toward labor, crop yields and total output decrease, crop prices increase, and welfare shifts from consumers to producers. Our model results indicate that, when faced with Kyoto Protocol induced energy price increases, farmers behave in much the same manner described in the above empirical studies.

Based on our review of literature, we found no published reports which estimate empirically the impact of the "oil crises" on regional cropping patterns and net revenues. Several factors make measuring these effects empirically difficult. During the 1970s and 1980s, several economic factors—more significant than increasing oil prices—were influencing the farming sector. Federal crop price support programs were providing generous, albeit distorting, payments tied to actual crop yields; foreign demand for U.S. grain was surging; and farm operations were becoming more energy efficient. These positive economic factors easily outweigh (and make it difficult to abstract empirically) the negative impacts of increasing energy prices on cropping patterns and net revenues. The economic studies which look at the impact of the energy price shocks on cropping patterns and farm revenues rely on simulation and programming models rather than empirical estimates. Tewari summarizes the findings of some of the leading studies done in the aftermath of the oil price jumps of the previous two decades.

The general farm economic conditions are sufficiently different today compared to the era of energy price shocks. Therefore, the lessons learned from those years have limited relevance to how the farm sector will fare under the Kyoto Protocol. In the past decades, all input prices (not just energy) were experiencing price inflation, and U.S. farm exports were growing more rapidly than they are today. The crop price support programs of the previous decades, which played a dominant role in farmers' decision making and net revenues, are no longer in existence. On-farm energy efficiency is much higher today than during the previous two decades (Cleveland; Uri and Day). In addition, more irrigation water was becoming available in the West during the 1970s, and the pumping depths in the Ogallala aquifer—which supplies much of the irrigation water in the plains states as well as the eastern portions of the mountain states—were shallower compared to conditions of the 1990s (Dugan and Cox). And finally, the price increases expected under the Kyoto Protocol are less than the fourfold energy price increase seen in the aftermath of the 1970s and 1980s oil crises.

There is a substantial literature on the effects of global temperature change on U.S. agriculture and of the economic effects on different sectors of reducing carbon emissions via a carbon tax or trading. However, we were unable to find a published study of the cost of carbon reduction on crop production in the U.S. One unpublished study by the American Farm Bureau reports a significant negative impact on the agricultural sector if the U.S. fulfills its global climate treaty obligations (Francl). The economic result of carbon taxes on welfare and sectoral production is generally analyzed using computable general equilibrium (CGE) models. Several models include explicit sectors for U.S. crop production. For example, Jorgenson and Wilcoxen project a small increase in 2020 agricultural output for a carbon tax level sufficient to maintain 1990 emission levels.

Boyd, Krutilla, and Viscusi estimated the net benefit of energy taxation to reduce emissions by comparing the costs of a carbon tax against the environmental benefits of emission reductions. Costs were determined by a CGE model with three sectors for agricultural production and a nested CES specification similar to that used in this study. The authors do not report their results by sector, but show net total welfare benefits to emission reduction. A CGE analysis was used by Alexander and Backus to calculate the effect of carbon taxes on the Minnesota State economy. When carbon taxes are used to offset other types of taxes, Alexander and Backus found that the overall effect on the state economy is relatively minor, and in some cases positive. Elkins reported a similar effect using a macroeconomic model of the United Kingdom economy. Comparing the results from three main global carbon abatement cost models, Fankhauser found that these models, for the most part, predict a less than 1% decrease in the GDP for the U.S. economy by year 2020 under a carbon tax imposed to stabilize emissions at 1990 levels.

The impact of global climate change on the entire U.S. agricultural sector has been addressed by several authors. Adams et al. provide a synthesis and review of the various approaches. They classify the economic response models into structural, spatial analog, and CGE models. The model used in the current study is a structural model in its specification of regional production and resource constraints, but has a nested CES production function specification that is used in most CGE models and calibrated in a similar manner. Our model therefore has the flexibility of unconstrained CES functions coupled with the specificity of regional crop production available from structural programming models.

Edwards, Howitt, and Flaim examined the impacts of a hypothetical increase in electricity prices on crop production and input substitution. Their method of analysis closely resembles ours; however, their regional focus is on only two states. In addition, they consider a much smaller increase in price of a single energy source (electricity), and apply it only to a single agricultural input (irrigation water).

Methodology

Farmers will react to higher energy costs in several ways. First, they are expected to substitute low-energy inputs (such as land, capital, and labor) for energy-intensive inputs (such as fertilizer, chemicals, and on-farm direct energy use). Second, they will reduce the acreage of energy-intensive crops in favor of less energy-intensive crops. Third, farmers will likely shift acreage from irrigated to dryland cultivation. Fourth, depending on the magnitude of the energy price increases and the profitability of the farm enterprises, in some regions the acreage of low-energy-using crops may also be reduced. This can occur when output price effects dominate input price effects. Furthermore, farmers' responsiveness to energy price changes will differ depending on the regional differences in profitability conditions and energy use.

All of these adjustments will take place in a highly interactive environment in which the changes in input use affect crop yields and, combined with the cropping pattern and acreage changes, also affect the total output of each crop produced and ultimately the market price of the crops. The changes in crop prices in turn influence input use, cropping choice, and planting decisions. To account for these interactions, the economic model employed in the analysis needs to be national in scope, embody regional crop production characteristics, and have the ability to explicitly account for farmers' input substitution behavior.

The Model

Many studies use computable general equilibrium modeling to simulate the effects of change in input prices on input use and output. A full CGE model of the U.S. agricultural sector, in the regional, crop, and input detail sought here, would be computationally infeasible. This study borrows from the CGE framework, but it is partial equilibrium in that its scope is limited only to the crop sector, with no direct linkage to other sectors in the economy.

The approach taken here is very similar to models used by Howitt (1995a, b), and by Edwards, Howitt, and Flaim. We start with the assumption that farmers are trying to maximize profits when they select the crop mix, acreage, and input levels. Farmers' economic behavior is modeled in a nonlinear programming framework. Each cropping activity is defined by a nested constant elasticity of substitution (NCES) production function with seven inputs as the arguments, allowing the model to endogenously determine the quantities of inputs used in each activity. The smallest decision-making unit is a region. There are 12 regions spanning the 48 contiguous states. Regions are modeled as aggregate farm units producing all the major crops in their respective areas under dry and irrigated conditions. The model incorporates aggregate (domestic and export) demand equations for each crop which endogenously determine crop prices.

The model simulates a conditional near-term sectoral equilibrium in a comparative static setting. Farmer behavior is predicted for given policy shocks in terms of acres allocated to specific crops in each region (with or without irrigation), the amount of each input used, and the impact on crop prices. More specifically, the model is defined by the following objective function and constraints.

Objective Function

The objective function represents the aggregate consumer (domestic and foreign) and producer welfare for all regions and activities:

$$\Pi = \sum_i \left[\alpha_i \sum_w \sum_r q_{iwr} + 0.5\delta_i \left(\sum_w \sum_r q_{iwr} \right)^2 \right] - \sum_i \sum_w \sum_r \tau_{iwr} q_{iwr} \tag{1}$$
$$- \sum_r \left[\nu_{r1} \sum_i \sum_w x_{iwr1} + 0.5\omega_{r1} \left(\sum_i \sum_w x_{iwr1} \right)^2 \right]$$
$$- \sum_i \sum_w \sum_r \eta_{iwr1} x_{iwr1} - \sum_i \sum_w \sum_r \sum_j \left(\rho_{iwrj} x_{iwrj} + \phi_{iwrj} x_{iwrj}^2 \right).$$

This formulation ensures a competitive market equilibrium solution. The first expression in brackets measures the area under the crop-specific linear market quantity-dependent demand equations, where α_i is the intercept and δ_i is the slope of the quantity-dependent demand equation for crop i. The variable q_{iwr}, described in equation (2) below, represents the output of crop i, produced under cultivation condition w (1 = dry and 2 = irrigated), in region r. The coefficient τ_{iwr} in the second expression accounts for the marketing and transportation costs of output produced. The third expression allows the land rents to be endogenous at the regional level, where ν_{r1} and ω_{r1} are the intercept and slope of regional linear land supply equations, respectively. The coefficient η_{iwr1} accounts for the difference between the regional average land rent and the crop activity-specific land rents in that region.

The last term in the objective function is a quadratic cost function, where ρ and ϕ are the coefficients, and the variable x_{iwrj} is the amount of input j ($j = 1, \dots, 7$, with 1 = land input) used in the cropping activity i, w, r. This function is quadratic in the land input and linear in the others. For the non-land inputs, ϕ_{iwrj} is zero and ρ_{iwrj} is the linear per acre cost c_{iwrj} for each input. The quadratic cost function serves two purposes. First, it captures the fact that as more land is allocated to a specific crop, marginal cost increases as marginal lands with lower yield potential come into production. Second, it allows for the exact calibration of the model solutions to the base year levels of crop acreage. This method of calibrating was first used by Howitt (1995a,b) in what he termed "positive mathematical programming" (PMP). The PMP approach eliminates the need to use upper- and lower-bound constraints on the activity levels when simulating policy scenarios.

Nested CES Production Function

The regional total output from each cropping activity q_{iwr} (indices are dropped for brevity) is defined by a nested CES type production function with seven categories of inputs:

$$Q = C\left\{\beta_F\left[C_F\left(\sum_{j=1}^{2}\beta_j x_j^{\gamma_F}\right)^{1/\gamma_F}\right]^{\gamma} + \beta_V\left[C_V\left(\sum_{j=3}^{7}\beta_j x_j^{\gamma_V}\right)^{1/\gamma_V}\right]^{\gamma}\right\}^{1/\gamma}. \tag{2}$$

The function consists of two nests. The first nest, expressed in the first set of brackets, includes the first two categories of inputs, the allocatable inputs of land and water. The second nest, expressed in the second set of brackets, is for the remaining five variable inputs. Each nest is in itself a CES function. A nested CES function is more flexible than a regular CES function in that more than one elasticity of substitution coefficient between inputs can be modeled. In agricultural crop production, the ability to substitute inputs varies significantly (Debertin, Pagoulatos, and Aoun; Hertel et al.; Rendleman; Ray). For example, the ability to substitute cultivation for herbicide weed control is greater than the substitution potential between water and nitrogen.

In the nested CES formulation, the nests can be thought of as hierarchies. Equation (2) has the higher nest parameters on the outside. The scalar C is the top-nest scale parameter, and β_F and β_V are the top-nest share parameters for allocatable and variable inputs, respectively. Moving to the lower nests, C_F and C_V are scale parameters for allocatable and variable input nests, respectively. The quantity of input j allocated to each cropping activity is indicated by x_j, where the j values of 1 and 2 correspond to allocatable inputs of land and water, and the remaining values of j (from 3 to 7) correspond to variable inputs. The parameter β_j is the share parameter of the jth input. In addition to index j, input quantity x is indexed over i, w, and r, which are dropped here for brevity. The coefficient $\gamma = (s-1)/s$, where s is the top-nest elasticity of substitution coefficient. Finally, $\gamma_F = (s_F - 1)/s_F$ and $\gamma_V = (s_V - 1)/s_V$, where s_F and s_V are the elasticity of substitution between the allocatable inputs and the elasticity of substitution between the variable inputs, respectively. For the dryland cropping activities, the allocatable input nest has only the land input as its argument.

Model Constraints

In the following discussion, indices on x are reintroduced: i (crop), w (irrigation condition), r (region), and j (input).

The regional irrigation water constraint limits the total irrigation water used by all irrigated crops ($w = 2$) in a region to the actual total irrigation water ($j = 2$) used in the region in the base year, $\overline{X}_{2r2}$. This constraint is specified as:

$$\sum_i x_{i2r2} \le \sum_i \overline{X}_{i2r2}. \tag{3}$$

Likewise, the regional irrigated land constraint restricts the total land allocated to irrigated cultivation to the total actual base year irrigated acreage:

$$\sum_i x_{i2r1} \le \sum_i \overline{X}_{i2r1}. \tag{4}$$

Constraint (4) is redundant in the base run. Since it is not needed in the calibration step, the right-hand-side value of this constraint is kept slightly above its actual base year value so as not to bind. It is included under policy shocks so that the irrigated land in regions will not exceed the base year levels.

In some arid regions, irrigated crop production occurs on land that has insufficient rainfall for dryland production. In these regions, dry cultivation is not an economically viable option for most of the crops grown under irrigated conditions. In the model, we include constraints to limit the availability of total dryland in these regions to be no greater than the actual base year dryland acreage.

Empirical Specification

The crops included in the model are barley, corn, cotton, hay, oats, rice, sorghum, soybeans, and wheat. These crops account for 94% of all harvested crop acreage in the U.S. in 1990 [U.S. Department of Agriculture (USDA) 1992]. The 12 U.S. regions are defined as follows: Appalachian (Kentucky, North Carolina, Tennessee, Virginia, West Virginia); Corn Belt (Illinois, Indiana, Iowa, Missouri, Ohio); Delta States (Arkansas, Louisiana, Mississippi); Lake States (Michigan, Minnesota, Wisconsin); Northeast (Connecticut, Delaware, Maine, Maryland, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont); Northern Plains (Kansas, Nebraska, North Dakota, South Dakota); Southern Plains (Oklahoma, Texas); Southeast (Alabama, Florida, Georgia, South Carolina); Northern Mountain (Idaho, Montana, Wyoming); Southern Mountain (Arizona, Colorado, Nevada, New Mexico, Utah); Northern Pacific (Oregon, Washington); and Southern Pacific (California). The regional delineation can be easily modified so that each region represents a state. However, this would mean more regions, and therefore much slower model solution times. With more regions also comes the possibility that the model fails to converge to an optimum solution due to numerical scaling problems.

The base year for the analysis is 1990, since this is the most recent year for which we could obtain complete data. The data on crop acreage, output, yield, and price are from the USDA/National Agricultural Statistics Service's (1992) *Agricultural Statistics*. For some states, the "Farm and Ranch Irrigation Survey" estimates were used to fill in the missing irrigated crop data (U.S. Department of Commerce). The data on input prices and quantities are extracted from the "Farm Costs and Returns Surveys" raw data files (various years) provided by the USDA/Economic Research Service.

The coefficients of the demand equations, α_i and δ_i, are derived by solving crop-specific linear demand equations, where a crop's aggregate demand elasticity and the base year aggregate market price and quantities are given. The demand elasticity estimate for hay is taken from Konyar and Knapp, and estimates from Green and Price are used for the remaining crops. The latter elasticity estimates include foreign as well as domestic demand for the crops in the model.[1,2] The coefficient τ_{iwr} is measured as the difference

[1] A high percentage of the crops included in the model are exported. For example, in value terms, 24% of barley, 38% of corn, 53% of cotton, 79% of rice, 66% of sorghum, 35% of soybeans, and 58% of wheat output were exported in 1990.

[2] The crop demand equations in the model account for the domestic and export demand of each crop, enabling us to measure the changes in U.S. crop exports when domestic crop prices increase. In our scenario, we are assuming that the crop demands stay constant. Theoretically, however, the Kyoto Protocol, when fully implemented, should also increase crop prices in the countries which trade in these crops with the U.S. As a result, we would expect an increase in the U.S. export demand (change in the price of a substitute good). In reality, the major importers of U.S. crops do not themselves grow any significant amount of the crops they import. Consequently, we do not expect a noticeable increase in the U.S. export demand from the Annex I countries when they fully comply with the protocol. The countries that grow as well as import from the U.S. the crops in question (China, India, Mexico, and the African states) are not in the Annex I group, and as such these nations have no carbon emission targets.

between the national market and the regional price of each crop in the base year. Implicit in the average national market price for each crop is the cost of transporting and marketing it, on average. As specified in our model, τ reflects the deviation of a region from the average transportation and marketing costs, and thus can be negative or positive. In the policy runs, the national-level market price for each crop is endogenously determined. During the solution, τ maps the national crop prices to their regional levels so that the deviation of regional crop price from the national average is maintained.

The coefficients of the regional land supply equation, ν_{r1} and ω_{r1}, are calculated by solving a region-specific linear equation, where the regional average land rents, land in crop production, and land supply elasticity are given. Supply elasticity is derived from a special run of a model presented in Lewandrowski et al. The coefficient η_{iwr1} is calculated as the difference between the crop-specific land rent in each region and the average land rent for that region.

The allocatable inputs in the model are land and irrigation water. The variable inputs are labor, capital, fertilizer, chemicals (pesticides and herbicides), and energy&other. Included in the energy&other category are such relevant inputs to this analysis as electricity and five different fuels used in farm machinery, irrigation pumping, and drying and ginning. These inputs account for more than half the costs in the energy&other category. The model's input categories can be further disaggregated if required by a specific policy analysis. This, however, would come at the expense of a much slower convergence to optimality.

The method of calculating the cost function coefficients ρ and ϕ (for land only) is based on Howitt's (1995b) PMP approach. Following is a brief description of the steps involved. First, a linear programming problem is solved. In this problem, the objective function is linear net profit. Output prices, regional resource use, and the acreage of each activity are constrained at their base year levels. From the solution, the shadow value of each activity-specific acreage constraint, λ, is obtained. The slope coefficient for each activity ϕ_{iwr1} equals $2\lambda_{iwr1}/x^*_{iwr1}$, where x^* is the base year acreage of the respective activity. To obtain ρ, we subtract λ from the per acre cost of the land input. For the non-land inputs, ϕ and λ are zero, so $\rho_{iwrj} = c_{iwrj}$ for $j = 2$–7.

The elasticity of input substitution coefficients of the nested CES function [equation (2)] are derived from several empirical sources. The values of the substitution parameter between land and water are obtained from a U.S. Department of Interior study. In this study, separate elasticities for truck crops, row crops, and alfalfa for California are estimated. Due to the lack of empirical estimates for the other states, and the fact that the range of irrigation technologies is similar across regions, we use the California elasticities for irrigated activities in all regions.

The input substitution parameter values for the top nest, i.e., the allocatable and variable inputs nest, and the substitution parameter for the inputs in the variable input lower nest 2, are based on results of Hertel et al., and Rendleman. Rendleman estimates own-price and cross-price elasticities of derived demand for several inputs used in the production of food grains, feed grains, oilseed crops, and cotton. His input categories, with the exception of energy&other, closely resemble ours. For the energy&other category, we rely on estimates from Hertel et al. From the Allen partial elasticities of substitution found in Hertel et al., and in Rendleman, we calculate Morishima elasticities of substitution. Morishima elasticities are relevant for the type of CES function we use here

(Blackorby and Russell). We weigh the pairwise Morishima elasticities by each input's cost share in the variable input nest to come up with a single crop- and region-specific elasticity of substitution for nest 2. The elasticities of substitution for the top nest, i.e., between allocatable and variable nests, are calculated in a similar fashion, using original estimates from the three empirical sources.[3]

The values of the remaining parameters of equation (2) (C, β_F, β_V, C_F, C_V, and β_j) are obtained by solving the first-order conditions of a profit-maximization problem defined by equations (1)–(4). The known quantities are elasticity of input substitution, base year levels of acreage, output, input use under each activity, and regional crop prices, along with shadow values of the regional land and irrigation water constraints. These shadow values are obtained from the solution to the earlier linear programming problem.

To summarize, in the first stage, a linear programming problem is solved. The shadow value estimates from the solution, along with input substitution coefficients and the base year levels of the variables, are used to calculate coefficients ρ and ϕ in equation (1) and coefficients C, β_F, β_V, C_F, C_V, and β_j in equation (2). In the second stage, the model defined by equations (1)–(4) is solved. The crop prices are endogenous in the second model. Both models are written in GAMS software and solved sequentially with the MINOS optimization algorithm on a PC (Brooke, Kendrick, and Meeraus). The base year solution of the second model exactly replicates regional base year acreage and input use in each cropping activity and output price. This is the model we use in the policy scenario.

Carbon Permit Price Impacts

We analyze the effects of instituting a carbon permit trading regime on input use, regional cropping patterns, crop prices, net revenue from crops, and consumer (domestic and foreign) surplus in the U.S. by comparing the static partial equilibrium simulation of the model under base year conditions with results of the simulation with higher energy prices.

Diesel, electricity, gasoline, LP gas, natural gas, and fuel oil are the commonly used energy sources in the cultivation and processing of crops, and in the manufacturing and distribution of fertilizers and chemicals. If a U.S.-wide carbon permit trading regime is implemented to fulfill the Kyoto Protocol's binding agreements (for the U.S., 7% below its 1990 carbon emission levels), the prices of these fuels and electricity are estimated to increase from 145% to 220% above their 1990 levels by the year 2010 (U.S. Department of Energy 1998, table B3). In the model's data set, the on-farm direct use of these fuels and electricity is disaggregated and explicitly included in the water and energy&other input categories. The percentage increases in the energy prices are then directly imposed on these inputs for the carbon scenario run.

The effects of energy price increases on the prices of the fertilizer and chemicals input categories are handled separately. Nitrogen, phosphorous, and potash are the main fertilizers used in commercial cultivation. We calculate the cost of energy used in the

[3] Our approach of using elasticities of substitution from empirical studies and calibrating the CES scale and share parameters is chosen because the elasticities of substitution are dimensionless measures of the inherent production technology, and thus they can validly be estimated a priori from other empirical studies and used in our calibration model. In contrast, the CES scale and share parameters have values which vary as a function of regional and crop production, and thus they cannot be accurately transferred from empirical studies to modeling studies.

manufacturing and distribution of these fertilizers, under the base year and under higher energy prices. The amounts of different fuels and electricity used in manufacturing and distribution are based on Bhat et al.; energy prices for the base year 1990 are from the "State Energy Price and Expenditure Report" (U.S. Department of Energy 1995); and adjustments to some of the fertilizer energy cost estimates are made based on the energy cost figures compiled by The Fertilizer Institute. Our estimates of the base year energy cost of manufacturing and distributing one pound of nitrogen, phosphate, and potash are \$0.066, \$0.044, and \$0.021, respectively. With the increased energy prices, these costs are recalculated and the net increases are \$0.096, \$0.031, and \$0.016 per pound, respectively.

Energy cost estimation for pesticides and herbicides requires additional steps. From the USDA's "Agricultural Chemical Usage" reports (various years), we calculate, by crop and by state, weighted average per acre amounts of chemicals most commonly applied in fields. These figures are multiplied by the amounts and prices of the different energy sources used in the manufacturing, packaging, and distribution of the same chemicals. Data on the energy content of chemicals are from Bhat et al. The calculations are repeated with increased energy prices, and the net increase in per acre chemical costs for each crop is obtained.[4] We assume that the full impact of the carbon scenario on energy prices and the subsequent increase in farm input costs occur in one year.

The results show that, when faced with higher energy prices, total crop acreage declines slightly, farmers adjust input mix and cropping patterns, and output prices increase, as does total net farm revenue. The substitution of land and other inputs for energy-intensive inputs (the third type of intensive margin of adjustment mentioned above), comes at the expense of lower yields, especially in the irrigated crops (refer to table 2).

To identify the initial impact of changing energy prices on costs, the percentage increases in per acre and per unit variable costs are calculated to reflect the change in variable costs before and after farmers substitute inputs and change cropping patterns. Figures in table 1 give crop-specific per acre and per unit variable costs under the base year cost conditions and the percentage change in these costs after energy prices increase but before farmers make adjustments. Similar information on per acre water, fertilizer, chemical, and energy&other costs is provided. The last two columns of table 1 show the percentage change in per acre and per unit total variable cost after farmers substitute inputs and reallocate acreage. As energy prices increase, dryland crops experience a 16% weighted average initial increase in per acre total variable costs, ranging from 8.7% for soybeans to 26% for cotton. With a weighted average of 31.5% increase across crops, the energy&other category of inputs bears the brunt of energy price impacts, followed by fertilizer inputs, which on average suffer a weighted average of 25% increase in cost across crops. The chemicals category is the least affected, with an average jump in costs of only 6.8%.

The initial impact of energy price hikes is more severe for the irrigated crop variable costs. Prior to input substitution and acreage adjustments, total variable cost increases by an average of 28% across irrigated crops, from a high of 47.2% for sorghum to a low

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[4] These estimates should be viewed as the lower limit on cost changes. We are unable to find energy use data for lime and manure, and for some of the chemicals that fall into pesticides, herbicides, and defoliants categories. In addition, data on energy use in custom operations are not available.

Table 1. Selected per Acre Variable Costs: Baseline Values and Percentage Change Under the Kyoto Protocol Scenario, Before and After Adjustments

	BEFORE ADJUSTMENTS							AFTER ADJUSTMENTS	
	Total Variable Cost			% Change				Total Variable Cost	
Crop Description	$/Acre	$/Unit [a]	% Change	Water	Fertilizer	Chemicals	Energy &Other	Per Acre % Change	Per Unit % Change
Dryland Crops:									
Barley	71.62	1.43	17.8	—	36.0	2.5	33.7	6.5	13.6
Corn	181.46	1.60	18.6	—	30.2	10.8	28.2	6.3	13.4
Cotton	227.34	0.48	26.0	—	26.8	5.3	55.8	6.5	19.2
Hay	99.47	46.81	14.6	—	18.8	0.0	39.9	7.0	11.4
Oats	59.75	1.00	19.2	—	22.7	0.0	34.0	5.0	13.3
Sorghum	85.31	1.46	17.9	—	34.2	11.6	31.7	7.2	13.2
Soybeans	120.57	3.56	8.7	—	15.4	5.3	27.8	0.8	4.6
Wheat	75.15	2.02	17.2	—	32.5	4.5	27.4	6.2	13.6
Irrigated Crops:									
Barley	169.52	2.05	25.0	64.8	29.8	2.5	21.5	-0.6	18.0
Corn	238.99	1.60	29.3	92.9	40.3	8.7	18.5	0.5	15.6
Cotton	444.15	0.51	34.7	76.5	26.5	6.0	57.2	-3.0	19.5
Hay	254.15	63.85	21.9	68.4	21.3	0.0	27.9	-12.0	9.9
Oats	130.91	1.38	29.1	69.7	33.4	0.0	57.4	-21.7	27.2
Rice	309.47	5.62	27.0	86.9	37.0	18.3	16.7	8.5	20.0
Sorghum	180.50	1.95	47.2	89.0	42.7	6.7	28.0	-18.6	25.2
Soybeans	142.80	3.76	25.6	95.5	17.6	6.3	25.5	-2.4	12.5
Wheat	175.83	2.55	35.8	89.7	27.5	3.1	17.9	-13.0	20.1

[a] Barley, corn, oats, sorghum, soybeans, and wheat output is measured in bushels; cotton in pounds; hay in tons; and rice in hundredweight.

of 21.9% for hay. This result is not surprising since irrigated crops have higher yields and thus require more energy for the same on-farm tasks compared to dryland crops, and the energy used for irrigation is substantial. This is especially true in areas where farmers rely primarily on ground water. Other studies have also found significant cost increases on irrigated farming when energy prices go up (Whittlesey and Herrell; Maddigan, Chern, and Rizy; and Sloggett and Mapp). Our estimates show that the Kyoto Protocol's initial impact on water variable cost is an average increase of 83% over all crops. Combined with higher percentage increases for fertilizer and chemicals, the average relative increase in total variable costs for all irrigated crops is 75% greater than the initial variable cost impact on dryland crops.

As noted above, the last two columns in table 1 show the percentage change in total per acre and per unit variable cost after farmers adjust to the energy price increases by substituting inputs and altering cropping patterns. Not surprisingly, the final impact of the energy price increase on per acre variable cost is much less than the initial impact. After farmers have a chance to react to higher energy prices, the total per acre variable cost for dryland crops increases by an average of only 5.3%, as opposed to the before adjustment average increase of 16%. And for irrigated crops, per acre variable costs actually decrease by an average of 5.3%. Farmers are able to realize such cost savings by reducing the acreage of the most severely affected crops and by substituting inputs. This results in lower yields and an increase in per unit variable costs, albeit at a substantially smaller percentage compared to the per unit cost increase before farmers adjust to energy price increases. For example, dryland crops see an 11.3% average final increase in per unit cost as opposed to a 16% initial increase. Corresponding results for irrigated crops are 15.9% and 28%, respectively.

Table 2 reports the effects of the Kyoto Protocol on acreage, yield, and output of crops. Overall, there is a fairly small decrease (0.6%) in the total acres harvested, or about 1.7 million acres. Dryland acreage increases by 4.1 million acres or 1.6%, while irrigated acreage shrinks by 5.8 million acres or 16.1%. The increase of dryland acres at the expense of irrigated acres was expected; irrigated crops face a much higher increase in variable costs, and hence much lower net returns. This result reflects one type of substitution inherent in the model, namely the extensive margin adjustment of crop production between crops, across regions, and between dryland and irrigated cultivation.

The crop-specific acreage changes show a somewhat larger variation. All crops, other than cotton and hay, experience a decrease, albeit small, in total acreage when faced with higher energy prices. With the exception of corn and oats, the dryland acreage of all crops increases, while the irrigated acreage of all crops decreases. Irrigated oats, sorghum, and especially wheat, lose more than 40% of their acreage. Irrigated oats is a marginal crop in almost all the regions in the U.S., and irrigated sorghum and wheat are grown in areas that rely heavily on ground water and consequently suffer from increased energy costs for pumping.

In contrast to a small reduction in the total crop acreage, the crop outputs decrease by a much larger percentage, ranging from 15.2% for cotton to 4.7% for soybeans (table 2). The difference is entirely due to a decrease in yields caused by input substitution and the shifting out of irrigated production. For most crops, yields decrease 8–12%. Cotton, with a 16.8% reduction, suffers the largest relative yield decrease, while soybeans have the smallest yield drop with 4.2%.

Table 2. Baseline Acreage, and Percentage Changes Under the Kyoto Scenario

Crop Description	Acreage Baseline (000s)	Acreage % Change	Yield % Change	Output % Change
All Crops:				
Barley	7,499	-0.1	-9.9	-10.0
Corn	66,952	-2.0	-7.7	-9.6
Cotton	11,498	1.9	-16.8	-15.2
Hay	61,557	1.3	-8.5	-7.3
Oats	5,940	-6.2	-8.5	-14.2
Rice	2,813	-3.9	-9.6	-13.2
Sorghum	9,079	-1.1	-11.7	-12.6
Soybeans	56,502	-0.5	-4.2	-4.7
Wheat	69,323	-0.7	-10.6	-11.2
Total	291,163	-0.6		
Dryland Crops:				
Barley	6,167	3.2	-6.3	-3.3
Corn	57,486	-1.0	-6.3	-7.3
Cotton	7,070	8.4	-10.7	-3.2
Hay	52,647	3.0	-4.0	-1.1
Oats	5,804	-4.9	-7.3	-11.9
Sorghum	7,827	5.4	-5.3	-0.1
Soybeans	53,647	0.2	-3.7	-3.5
Wheat	64,337	3.3	-6.5	-3.5
Total	254,985	1.6		
Irrigated Crops:				
Barley	1,332	-15.2	-15.8	-28.6
Corn	9,466	-8.0	-13.0	-20.0
Cotton	4,428	-8.5	-18.9	-25.7
Hay	8,910	-8.9	-19.9	-27.0
Oats	136	-59.2	-38.5	-74.9
Rice	2,813	-3.9	-9.6	-13.2
Sorghum	1,252	-41.6	-35.0	-62.0
Soybeans	2,855	-13.3	-13.3	-24.8
Wheat	4,986	-52.4	-27.6	-65.5
Total	36,178	-16.1		

Irrigated crops experience a much larger relative drop in both acreage and yield, and hence output, compared to dryland crops. Some irrigated crops, such as oats, sorghum, and wheat, show yield decreases of well over 25% and, combined with large acreage reductions, the total output for these irrigated crops falls more than 60%. The irrigated crop acreage accounts for only 12% of all crop acreage in the U.S. in 1990. But because irrigated crops have much higher yields (for most crops more than 80% above dryland yields), the changes in the irrigated acreage and yields have a notable impact on overall crop output.

The significant drop in the irrigated crop output actually gives a boost to farm net returns in general (table 3). While net revenue generated from all irrigated crops declines

Table 3. Base Year Net Revenue, and the Relative Changes in Net Revenue, Consumer Surplus, Welfare, and Output Price Under the Kyoto Scenario

Crop Description	Net Revenue ($000s)	Net Revenue % Change	Consumer Surplus[a] % Change	Social Welfare[b] % Change	Market Price[c] ($)	Market Price % Change
All Crops:						
Barley	231,643	-0.7	-19.0	-13.9	2.15	13.3
Corn	5,482,128	0.5	-18.3	-12.6	2.29	13.3
Cotton	1,286,127	0.1	-28.1	-19.7	0.67	19.0
Hay	3,487,825	2.4	-14.1	-9.0	74.59	10.5
Oats	56,400	8.5	-26.3	-19.9	1.17	16.7
Rice	169,515	-13.8	-24.6	-22.5	6.71	18.0
Sorghum	328,558	8.8	-23.6	-13.4	2.13	14.8
Soybeans	4,147,252	3.4	-9.2	-4.7	5.73	6.3
Wheat	1,456,946	8.9	-21.2	-14.0	2.62	14.4
Total	16,646,396	2.3	-17.1	-11.1		
Dryland Crops:						
Barley	169,119	12.2				
Corn	4,436,054	4.2				
Cotton	593,898	17.0				
Hay	2,695,575	9.2				
Oats	56,003	10.1				
Sorghum	305,269	17.5				
Soybeans	3,931,742	5.2				
Wheat	1,401,105	12.9				
Total	13,588,765	7.4				
Irrigated Crops:						
Barley	62,524	-35.7				
Corn	1,046,074	-15.4				
Cotton	692,230	-14.4				
Hay	792,251	-20.7				
Oats	397	-223.5				
Rice	169,515	-13.8				
Sorghum	23,289	-104.7				
Soybeans	215,510	-29.3				
Wheat	55,841	-93.3				
Total	3,057,631	-20.0				

[a] Consumer surplus includes domestic and foreign demand.
[b] The welfare change measures only the net change in consumers' and producers' surplus.
[c] The market price is per bushel for barley, corn, oats, sorghum, soybeans, and wheat; per pound for cotton; per ton for hay; and per hundredweight for rice.

by 20% (and much higher for some of the individual crops), their dryland counterparts enjoy a combined 7.4% increase in net revenue. In terms of actual net revenue, the irrigated hay, corn, and cotton farmers suffer the biggest losses, while the dryland farmers of hay, soybeans, corn, and wheat experience the largest net revenue gains. On balance, total net revenue from crop farming increases by 2.3%, or roughly $390 million, with soybeans, wheat, hay, sorghum, and corn (in that order) benefitting most from the Kyoto Protocol. This result contradicts the argument often made by critics of greenhouse gas abatement efforts, i.e., such attempts will impose a negative financial burden on businesses (Francl; Gattuso; Sutherland; WEFA, Inc.).

Table 4. Total Input Use, Output Price, and Relative Changes Under the Kyoto Scenario

			% Change Due to:	
Input Use	Baseline Input Use	Total % Change	Extensive Margin Adjustment	Intensive Margin Adjustment
Land (000 acres)	291,163	-0.6	-0.6	9.4
Water (000 acre-feet)	59,258	-46.9	-14.5	-24.4
Fertilizer (000 pounds)	34,459,830	-17.8	-1.6	-8.3
Chemicals ($000s)	3,849,669	-4.9	-0.9	4.5
Capital ($000s)	4,055,664	-1.2	-1.9	8.7
Labor (000 hours)	385,032	-2.4	-1.2	7.4
Energy&Other ($000s)	12,158,620	-21.2	-1.8	-12.4

Table 3 shows that if the Kyoto Protocol is implemented, crop prices will increase from 6.3% for soybeans to 19% for cotton. The increase in crop prices, combined with the sizeable decrease in crop production, lowers consumer surplus (domestic and foreign) from all crops by 17.1%. The largest relative damages occur to the consumers of cotton and oats. But in absolute terms, corn buyers suffer the most damage to their surplus followed by the hay, wheat, and cotton consumers. Even with the increases in net farm income for most of the crops, social welfare from all crops decreases by a total of 11.1%.

The increase of net farm revenues in the face of significant energy price hikes can be attributed to two distinct effects: first, cost-saving input substitution, crop substitution, and regional acreage shifts; and second, revenue-enhancing endogenous price changes. These effects differ substantially across inputs and regions, as well as crops.

The extent of the overall input substitution can be gleaned from table 4. The first numeric column gives the input use in the base year. The second column shows the percentage change in input use after farmers make the extensive and intensive margin adjustments in reaction to energy price increases. The numbers (in percentage change) show that the use of energy-intensive inputs declines relative to other inputs when energy prices increase. The degree of the relative changes in input use is commensurate with the energy intensity of these inputs; the largest movement is away from irrigation water (46.9%), followed by energy&other (21.2%), fertilizer (17.8%), and chemicals (4.9%). If farmers, in the face of energy price increases, change cropping patterns and regional acreage but do not substitute inputs (i.e., only make the extensive marginal adjustment), then there is a much smaller decrease in the use of energy-intensive inputs. These changes are shown in the third numeric column and can be interpreted as the change in input use due to output and price effects. For example, without input substitution, irrigation water use would decrease by 14.5%, as opposed to a full decrease in water use of 46.9% occurring under input substitution. Energy&other and fertilizer inputs also would register a much smaller decrease in use if farmers did not substitute inputs.

The last column in table 4 shows the changes in input use attributed roughly to pure input substitution. We take each crop's per acre input use in the base year and under the full scenario, and normalize them by crop yields. Although crop acreage and yields change under the scenario, expressing the input use in terms of crop yield allows us to maintain the assumption of constant output and permits us to come up with a measure of input substitution. We then calculate the percentage difference and take the weighted average over the crops for each input. A more exact measure of input substitution, in the traditional sense, is not possible as crop outputs are measured in different units; thus we are forced to work with weighted average relative terms. The results appear in the final column. The figures suggest that input substitution, rather than changes in acreage, is largely responsible for the total change in input use. As expected, the energy-intensive inputs (water, energy&other, and fertilizer) register the largest relative decreases in use. Since the increase in the cost of chemicals is small relative to other energy-intensive inputs, we observe that this category of inputs is substituted for its more energy-intensive counterparts.

Another way of capturing the significance of input substitution is by measuring the effect of the Kyoto Protocol on net revenue with and without input substitution. When the Kyoto Protocol scenario is simulated with the input proportions constant at the base year level but acreage and output prices vary, the lack of input substitution results in a decrease of 14%, or nearly $2.5 billion, in net revenues from all crops. In contrast, when input substitution, along with acreage adjustments, is taken into account, the result is a net revenue increase of 2.3%, or $390 million. The 16.3% difference in the net revenues between the two simulations suggests that input substitution is a critical factor in mitigating the energy price increases, and hence in helping to assure the economic viability of crop farming. In the absence of input substitution, total crop acreage is estimated to decline by 5.8% as opposed to a 0.6% decrease under our standard scenario. Models that do not account for input substitution will overestimate acreage decreases and miscalculate the revenue impacts under similar energy price shocks.

The endogenously determined output prices play a significant role in the impact on net revenues. Demand elasticities of the crops included in the model are inelastic and range from 0.7 to 0.85. When energy prices go up, there is a noticeable drop in crop production and a consequent increase in the market prices of all crops (table 3). The price increases range from 6.3% for soybeans to 19% for cotton, with other prices increasing by more than 10%. Higher prices combined with inelastic demands lead to a higher total revenue for all crops, which helps explain why (except for rice and barley) net revenues go up in the face of energy price increases.

The magnitude of acreage and net revenue impacts is quite different among the 12 regions of the study (table 5). Regions which rely heavily on irrigated crop production and ground water for irrigation tend to experience a greater decrease in total acreage and net revenues. The Delta States, Southern Pacific, Northern Mountain, Southeast, Southern Mountain, and Southern Plains regions are highly affected in this regard, with the Southeast and Southern Mountain regions suffering the most. Crops grown in these two regions generally have low net returns due to below-normal yields compared to the other regions. In the Corn Belt, Lake States, Northern Plains, and Northern Pacific regions, both total crop acreage and net revenue show high increases. These four regions rely very little on irrigation and/or have above-normal yields in dryland crops, and consequently they benefit (in terms of both acreage and net revenue) at the expense of those regions with lower yields and profitability.

Table 5. Baseline Regional Acreage and Net Revenue and Percentage Changes Under the Kyoto Scenario

Region Description	Baseline All	% Change	Baseline Dryland	% Change	Baseline Irrigated	% Change
Acreage (000 acres):						
Appalachian	16,256	-0.2	16,253	-0.2	3	-54.9
Corn Belt	79,487	1.5	78,551	1.7	936	-13.2
Delta States	16,847	-3.8	12,317	-1.1	4,530	-11.0
Southern Pacific	4,119	-6.6	530	1.0	3,589	-7.7
Lake States	31,005	2.3	30,485	2.3	520	1.0
Northeast	9,644	-0.6	9,600	-0.5	43	-17.9
Northern Mountain	13,715	-1.6	9,153	6.8	4,563	-18.5
Northern Plains	71,087	2.2	61,502	4.4	9,585	-12.1
Southeast	7,263	-7.4	6,922	-6.3	341	-28.2
Southern Mountain	8,310	-10.3	3,512	1.0	4,798	-18.6
Southern Plains	27,469	-9.7	21,974	-3.7	5,495	-33.9
Northern Pacific	5,961	1.8	4,184	4.3	1,777	-4.3
Total	291,163	-0.6	254,985	1.6	36,178	-16.1
Net Revenue ($000s):						
Appalachian	666,956	1.1	666,888	1.1	68	-93.7
Corn Belt	6,389,314	6.3	6,317,225	6.5	72,089	-12.9
Delta States	782,715	-9.2	445,528	2.4	337,187	-24.7
Southern Pacific	572,636	-14.6	37,378	4.7	535,259	-15.9
Lake States	2,108,236	8.3	2,036,770	8.7	71,466	-2.8
Northeast	837,136	4.2	835,397	4.4	1,734	-104.2
Northern Mountain	420,040	-4.6	144,666	17.6	275,374	-16.3
Northern Plains	2,937,985	6.0	2,041,432	15.5	896,553	-15.9
Southeast	62,850	-44.5	36,518	-53.9	26,333	-31.4
Southern Mountain	408,120	-28.4	97,458	6.1	310,662	-39.1
Southern Plains	1,067,196	-10.2	741,240	-0.3	325,956	-32.5
Northern Pacific	393,210	5.5	188,267	15.0	204,943	-3.2
Total	16,646,396	2.3	13,588,765	7.4	3,057,631	-20.0

Summary and Conclusions

In this article, a mathematical programming model of U.S. crop production with input substitution was developed. The model was used to simulate the effects of the likely increase in energy prices, under the Kyoto Protocol, on regional crop production, input use, output prices, and net revenues. The model's ability to explicitly account for farmers' input substitution behavior, regional crop production, and endogenous prices was instrumental in capturing the flexibility inherent in the crop production sector. Compared to models without input substitution, our model's estimates are believed to be a more realistic measure of what could actually occur if energy prices increase to the levels predicted by the Department of Energy.

The results indicate that, when faced with large energy cost increases, farmers substitute inputs and crops; high-energy-using inputs and cropping practices give way to less energy-intensive inputs and crops; acreage expands in the high crop yield regions; and, overall, cropping patterns among regions change. The ability to substitute inputs, combined with higher crop prices, results in an overall increase in net revenues, with dryland producers receiving all the benefits at the expense of their irrigated farming counterparts. There was a small decrease in total crop acreage, with all irrigated crops decreasing in acreage and increases in dryland acreage picking up most of the slack.

Our findings show that crops and regions are differentially impacted. When energy prices increased, some regions and crops suffered and other crops and regions benefitted in terms of acreage and net revenue. Overall, however, net revenue to crop farming actually increased as energy prices increased. Our results contradict the argument often made by critics of global warming treaties that the reduction of carbon emissions can only occur at the expense of business profits, including farming. Our results also show that, as crop prices increase and output decreases under the scenario, the cost to consumers exceeds the benefit to farmers from higher energy prices. The net social cost to farmers and consumers is negative.

Before a final judgment can be made concerning our scenario's impact on the social welfare vis-à-vis crop production, the potential environmental benefits of the Kyoto Protocol should be considered. There certainly will be measurable benefits to the environment within the confines of crop production. Such benefits are likely to come as farmers substitute low-energy-using inputs and crops for high-energy inputs and crops, decrease acreage and therefore abate some soil erosion, and reduce on-farm total direct and indirect energy use.

The model could be extended in several other ways in future research. Our analysis has omitted fruit, nuts, and vegetable crops. While these crops account for only 2% of all harvested crop acreage in the U.S. in 1990 (U.S. Department of Agriculture 1992), their share in the total farm revenue, at $13.8 billion, is much higher. More importantly, these crops rely heavily on energy use, and therefore they are likely to be influenced significantly by energy price hikes. Including them in the existing model of field crops, however, is not the best way to account for their interactions with energy prices as these crops are rarely substituted for field crops, and vice versa. But there is a strong case for applying our approach to model the fruits and nuts separately. The model does not include the livestock sector, and we can make the same argument that there is a good reason for building a separate model to address this sector.

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